A High-Speed Network for Cardiac Image Review

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A high-speed fiber-based network for the transmission and display of digitized full-motion cardiac images has been developed. Based on Asynchronous Transfer Mode (ATM), the network is scaleable, meaning that the same software and hardware is used for a small local area network or for a large multi-institutional network. The system can handle uncompressed digital angiographic images, considered to be at the "high-end" of the bandwidth requirements. Along with the networking, a general-purpose multi-modality review station has been implemented without specialized hardware. This station can store a full injection sequence in "loop RAM" in a 512 x 512 format, then interpolate to 1024 x 1024 while displaying at 30 frames per second. The network and review stations connect to a central file server that uses a virtual file system to make a large high-speed RAID storage disk and associated off-line storage tapes and cartridges all appear as a single large file system to the software. In addition to supporting archival storage and review, the system can also digitize live video using high-speed Direct Memory Access (DMA) from the frame grabber to present uncompressed data to the network. Fully functional prototypes have provided the proof of concept, with full deployment in the institution planned as the next stage.

INTRODUCTION

This paper describes the implementation of a prototype of the **Cardiac Image Network**, a high-speed network for multi-institutional sharing and viewing of full-motion cardiac images. Using Asynchronous Transfer Mode (ATM) networking, a scaleable approach to real-time image review over local- and wide-area networks is now possible. The design of the full network is presented, and the results of the initial laboratory prototypes described. This technology permits diagnostic-quality full-motion cardiac studies to be accessed and reviewed at distributed sites, as easily as current lab reporting systems.

DESIGN GOALS

The specific goals of the project are to:

- Deploy a comprehensive, fully scaleable ATM network for high-speed transmission and interactive review of full-motion image sequences
- Implement a file server with a virtual file system to handle on-line (high-speed disk), near-line (mounted tapes), and off-line (on the shelf) storage
- Develop a multi-modality cardiac image review station capable of receiving and displaying uncompressed image data at 30 frames per second (bandwidth requirement of 7.5 megabytes per second using 8-bit pixels and 512 x 512 images)

Several aspects of the Cardiac Image Network are particularly noteworthy, in contrast to other approaches:

- The public utilities can be used to extend the network, smoothly integrating local (LAN) and wide-area networking (WAN) functions.
- High bandwidths can be achieved, supporting real-time image display without compression. The same network design can be scaled down for lower bandwidth applications (such as traditional image archiving systems).
- It is designed to improve the allocation of medical resources and accelerate appropriate cardiac care. It should have an immediate and direct effect on health care delivery and costs.
- The design is fully scaleable, suitable for both large and medium-sized institutions. While designed for images initially, the database can be easily extended for handling non-image data.

ASYNCHRONOUS TRANSFER MODE

Asynchronous Transfer Mode (ATM) networking is an emerging standard for simultaneous handling of video, voice, and data [1]. It is central to the design of the Cardiac Image Network, and has several distinct advantages over previous networking approaches:

- ATM network is based on a network of switches and dedicated host links, so aggregate bandwidth increases as hosts are added. Shared media LANs, on the other hand, can saturate with just a small number of hosts, and have a greater cost since statistical aggregation of trunks is lacking.
- ATM offers an open-ended growth path, not locking into a single physical medium. Different systems can use the same format, interconnecting LANs, switches, and public networks. This permits a network design strategy that makes use of

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existing facilities while providing a smooth growth path as components are upgraded.

- Previously, the protocols to implement a Local Area Network (LAN) were different from those used for a Wide Area Network (WAN). ATM, on the other hand, uses the identical protocols (same cell format) for both LANs and WANs, thereby eliminating the artificial barriers between them.

ATM offers the following desirable design characteristics:

- The protocols for interfacing with user applications are based on published industry standards [2].
- Commercial products use ATM to connect workstations, and to do the necessary switching. Fully functional networks can be implemented now, without waiting for full deployment of large ATM switches by the public utilities.
- The technology is fully scaleable. Small prototype systems developed to provide ATM services within a single location can be extended to provide services between locations.

Final details of nation-wide ATM deployment have not been finalized (carrier-to-carrier interconnection, fully switched circuits, etc.). Current systems still permit full use of ATM advantages in a metropolitan area, using "switched virtual circuits" tunneled within dedicated fiber lines.

PREVIOUS WORK

NYNEX Media Broadband Services

NYNEX has developed a network-based multimedia communications to support collaborative work between users at geographically remote locations [3], and trial of the NYNEX Media Broadband Services (MBS) was recently completed at several hospitals in Boston [4]. MBS and its MEDOS operating system are proprietary, rather than being built on industry standards, and the software is currently only available on a limited number of hardware platforms. High-speed applications and video services have not yet been demonstrated. The collaborative review of coronary angiograms developed as part of these trials uses a synchronized control scheme (local and remote viewers synchronized over the network), rather than achieving real-time data transmission.

Project Zeus

Washington University has completed a technical feasibility project creating an ATM network for their campus, referred to as Project Zeus [5]. This project confirms the technical feasibility of ATM networking concepts, and has provided an important platform on which to build applications. Unfortunately, much of the hardware development for Project Zeus was based on a computer company that is no longer selling workstations. The video that was demonstrated was based on a JPEG coder-decoder, and is not appropriate for the diagnostic imaging project we are proposing.

Sony CineNet

This is primarily a digital video distribution system, based on the RP-125 digital video standard. This is at the center of Duke's digital angiography archiving program [6]. While the video is transmitted digitally, the result is not a general-purpose computer network, and no "out of band" communications are possible over the network. An additional computer network would need to be added to implement the virtual file system and other control functions. Wide Area Network strategies may be possible, but only by sacrificing the many advantages of ATM listed previously.

Review Stations

Several workstation-based systems have been described for the presentation of image or multimedia information [7,8]. These systems were not intended to be used for real-time display of high-resolution motion sequences, or for high-speed network interfacing. We have previously reported on the development of a personal review station for digital angiography. The system was designed to expand to handle full-motion uncompressed studies, but currently uses JPEG compression to compensate for the relatively slow speed of existing devices [9]. The review station has been demonstrated for the viewing of images from optical and magnetic disk, and high-speed tapes.

High-Speed Medical Image Networks

Several high-speed networks have been reported for Picture Archiving and Communications Systems (PACS) functions [10,11] and image review, but the reported bandwidths are still well below those required for cardiac imaging [12]. A parallel operating image buffer system has been used to increase the effective speed [13], but still could not break through the speed requirements. The implications of Wide Area Networks for image transmission has been examined [14], but with the exception of Project Zeus, none have looked at the ATM technology.

Network-Based Image Archives

The PACS system currently running at UCLA is considered to be large-scale [15], generating an average of 2 gigabytes a day of image data. By comparison, the digital output of a medium-sized

cardiac catheterization laboratory is 4 to 8 gigabytes per day (assuming 8 patients per workday, and 0.5 to 1.0 gigabytes per patient). The archival requirements for the Cardiac Image Network are clearly at the "high end" of what is currently implemented.

NETWORK DESIGN

Fully Scaleable ATM Network

The Cardiac Image Network is designed to provide integrated access to real-time and archived multi-modality image data. To fully achieve this objective, it must be possible to convey digital image data in real-time among several target hospitals. The nature of ATM technology allows network development to be based at a single site, with the same hardware and software capable of connecting several sites as the public utilities ATM switches are installed.

The basic elements of the approach for a single site are presented in Figure 1. The File Server uses a Unix workstation running a commercially-available Virtual File System (VFS) and a large-capacity RAID disk. The VFS makes a series of disks, tapes, cartridges, and other on-line and off-line storage media all appear as a single contiguous file system to the software. The details of migrating files on and off of the high-speed RAID disk are all handled by the VFS.

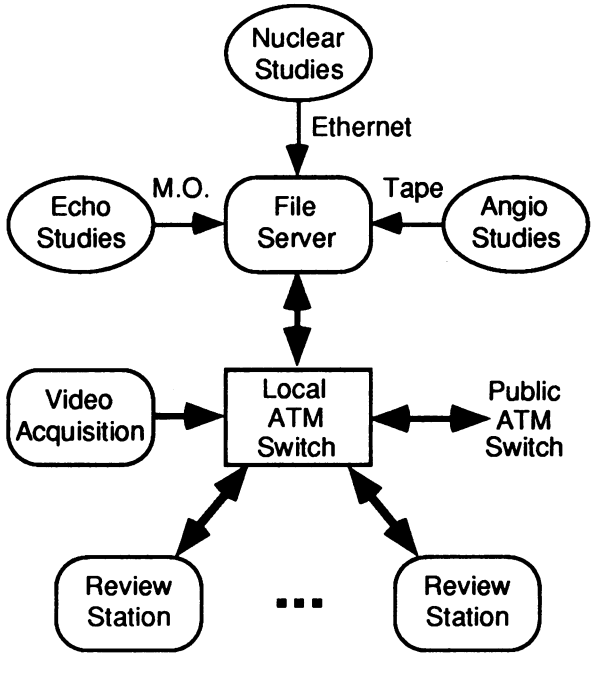

Figure 1: Cardiac Image Network at a single site (bold arrows are ATM connections).

Only the pathways for image data are shown; other non-image data (lab values, reports, etc.) could be handled in the future, but are not part of the initial system implementation. Nuclear cardiology studies are available by a direct Ethernet connection. The echocardiographic studies are read from a magneto-optical disk, and angiographic studies are imported from computer tapes.

More sophisticated electronic interfaces to external imaging systems are anticipated, and can be implemented using a workstation with an ATM adapter added to the network. The video acquisition module acts in this manner, digitizing video and making it available on the ATM network.

Network Design

Each node in a fiber-based ATM network is interconnected by a high performance "contentionless" switching array. This switching fabric permits the addition of connections without any degradation in network performance. The ATM network requires a central switch, station adapters for the workstations and the fiber optic connections from computer systems back to the switch. Our prototypes were implemented with commercially-available components. A standard ATM switch cluster provides a 2.5 gigabit per second switching array, can accommodate up to 16 network connections, and features support for standard network routing and data transmission (TCP/IP). Workstations are connected to the network using interface adapters that connect to the EISA bus.

Multi-Modality Review Workstations

The prototype software for angiographic review has been implemented using X-windows and Motif on a Hewlett Packard 735 workstation. Customized display software permits grayscale images to be stored in the workstation RAM at their native 512 x 512 resolution, then be interpolated up to 1024 x 1024 and displayed at 30 frames per second. Additional display controls allow setting of brightness, contrast, gamma settings, and edge enhancement. Similar software has been developed for the display of echocardiographic images (originating on a magneto-optical disk storage system that is part of the Hewlett Packard Sonos 1500 system used for clinical studies).

The review station is a client on the network, and communicates with a server managing the image files. Control messages between client and server uses the UDP layer (thereby permitting "many-to-one" connectionless service), while file transfers use the TCP/IP layer (connection-oriented). Virtual file

system software on the server manages the migration of image files between on-line storage (RAID disk), near-line storage (tape or optical drives), and off-line storage (unmounted cartridges on the shelf).

Real-time Image Acquisition
A commercially available frame-grabber with programmable phase-lock loop capabilities has been integrated into the network (no additional time-base corrector is needed). The system can acquire video signals and transfer them to the host computer using high-speed Direct Memory Access (DMA).

Industry Standards and Portability
Whenever possible we have sought to eliminate hardware dependencies and make the software portable to a variety of platforms. The following industry standards have been used in the design of the system:

- Unix Sys/V Operating System, X11 windowing system, Motif Graphic User Interface, and ANSI C programming language
- Asynchronous Transfer Mode ATM network transmission layer
- Transmission Control and User Datagram Protocols (TCP/IP and UDP/IP) networking protocols. TCP/IP provides a connection-oriented reliable delivery service on top of ATM to provide data to review stations. UDP/IP provides service for low-priority loss-tolerant traffic for low-bandwidth administrative functions.

Initial Prototype
As proof of concept, we have developed a prototype client-server application based on these designs This prototype initially ran with a dedicated ATM link between two workstations, and has now been extended to allow several review stations to connect to the server through an ATM switch (refer to Figure 1, above). The prototype has been used to evaluate the performance of several of the critical system components. We have confirmed the following performance using uncompressed image data:

- **Screen Rendering:** 512 x 512 8-bit images can be interpolated to 1024 x 1024 and displayed at 33 fps. Faster performance has been achieved on a newer workstation, but only 30 fps is required (traditional viewing rate for digital angiography).
- **Video Acquisition:** This has also achieved 30 fps using Direct Memory Access (DMA) to transfer from frame grabber to host memory.
- **ATM Transfer Rate:** The TCP/IP protocol used has approximately 40% overhead, but still sustained 64 megabits/second rates between the server and the client (60 megabits/second need to transmit a 512 x 512 8-bit image at 30 fps).

FULL NETWORK DEPLOYMENT

A full client-server based implementation of the network system has been completed, as described above. The Virtual File System (VFS) allows the client to access the entire patient library as if it was a large on-line file system (the VFS handles the migration of large data files between disks, tapes, and shelves). Plans for full deployment within one institution are now being completed. Planning with the local telecommunications company has also begun, with plans being finalized for an ATM switch to be installed in the central office shortly.

The extension of the Cardiac Image Network to connect multiple institutions is shown in Figure 2. Each hospital's local ATM switch and network remain intact, with the local ATM connected to the public ATM. Network addressing is resolved using the standard IP addressing scheme, so that no change in the local software or hardware is needed.

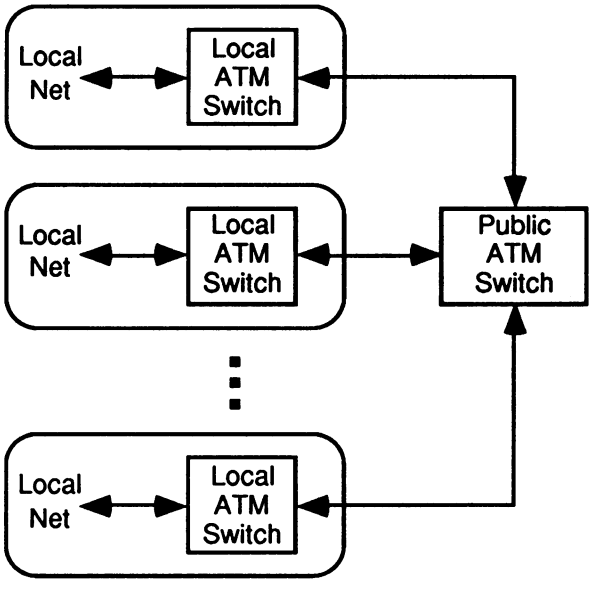

Figure 2: Multiple hospitals interconnected with public utility ATM switches

Studies are planned to look at the impact of the network on patient care within a single facility (using a multi-modality review station on the Coronary Care Unit to review echocardiograms, thallium studies, and coronary angiograms). Once the service is extended to affiliated hospitals, a study will examine the im-

pact of the network on resource utilization. This is especially timely as new cardiac catheterization laboratories at several of the affiliated hospitals perform diagnostic studies only; patients are transferred for angioplasty or coronary artery bypass surgery. The ability to review images "live" (with the patient still in the cath lab of the referring hospital) should help with scheduling of limited resources at the receiving hospitals. Finally, it is planned to use the video acquisition capabilities of the network to allow review of echocardiographic video tapes and coronary catheterization films between hospitals. Patients often have diagnostic studies at one hospital and are then subsequently admitted emergently to another hospital (the ambulance stopping at the closest hospital), providing a need to transmit diagnostic studies between hospitals on an urgent basis. The Cardiac Image Network provides the technology to do this.

SUMMARY

A high-speed network for the storage, transmission, and review of full-motion cardiac image studies has been developed. This represents a significant advance in speed and image quality over what has been previously demonstrated; we have achieved 30 frames per second with no image-degrading compression. The system addresses the highest end bandwidth requirements needed to care for acutely ill cardiac patients. The emerging availability of ATM technology by the public utilities means that ATM networks can be extended between institutions with no change of underlying hardware or software. Economies of scale can be appreciated by using a central site for the massive data storage, while using a client-server model to present patient information at local review stations. The prototypes that have been developed will shortly be extended throughout the hospital, and among several hospitals when the public ATM switch goes on-line.

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